The ambient acoustic environment in Laguna San Ignacio, Baja California Sur, Mexico

Kerri D. Seger[a)] and Aaron M. Thode
Scripps Institution of Oceanography, University of California San Diego, 9500 Gilman Drive, Mail Code 0206, La Jolla, California 92093, USA

Steven L. Swartz
Cetacean Research Association, 14700 Springfield Road, Darnestown, Maryland 20874, USA

Jorge Urbán R.
Laboratorio de Mamiferos Marinos, Universidad Autónoma de Baja California Sur Carretera Sur, km 5.5, Apartado Postal 19-B, 23080, La Paz, Mexico

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Each winter gray whales (*Eschrichtius robustus*) breed and calve in Laguna San Ignacio, Mexico, where a robust, yet regulated, whale-watching industry exists. Baseline acoustic environments in LSI's three zones were monitored between 2008 and 2013, in anticipation of a new road being paved that will potentially increase tourist activity to this relatively isolated location. These zones differ in levels of both gray whale usage and tourist activity. Ambient sound level distributions were computed in terms of percentiles of power spectral densities. While these distributions are consistent across years within each zone, inter-zone differences are substantial. The acoustic environment in the upper zone is dominated by snapping shrimp that display a crepuscular cycle. Snapping shrimp also affect the middle zone, but tourist boat transits contribute to noise distributions during daylight hours. The lower zone has three source contributors to its acoustic environment: snapping shrimp, boats, and croaker fish. As suggested from earlier studies, a 300 Hz noise minimum exists in both the middle and lower zones of the lagoon, but not in the upper zone.
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I. INTRODUCTION

A. Overview

The gray whale (*Eschrichtius robustus*) is a coastal baleen whale species whose modern range spans the North Pacific Ocean. The dominant Eastern North Pacific population breeds and calves during the winter months in lagoons along Baja California, Mexico, where it migrates from summer feeding grounds in the Bering, Beaufort, and Chukchi Seas (Poole, 1984; Swartz, 1986). Laguna San Ignacio (LSI) is one such lagoon where wintering whales aggregate.

The lagoon is located halfway down the Pacific side of the Baja California peninsula. It is surrounded by flat desert and experiences strong sea breezes averaging 12 m/s with 15 m/s gusts (Guerra *et al.*, 2010). The depth of the entrance is usually 28 ± 1 m but is known via traditional local knowledge to experience strong tidal flows that fluctuate up to 6–8 m during spring tides (Jones, 1981). As a result, large silt movements are capable of burying 0.5 m-tall lobster pots in a single day (Perez Bastida and Ramirez Gallegos, 2015). Moving northward, away from the mouth, the lagoon becomes shallow and rocky, interspersed with silty patches. Long, sandy ridges, called "bajos," are as shallow as 7 m and occur halfway between the mouth and northern-most boundary of LSI (Swartz and Urbán, 2014).

Following conventions set forth by Jones and Swartz (1984), this project divided the lagoon into upper, middle, and lower geographic "zones" (Fig. 1). The upper zone encompasses the northernmost 18 km of the lagoon; moving south from here, the middle zone ends at Punta Piedra (a local landmark at the narrowest point of the lagoon), about 7.5 km further down from the upper zone's boundary. The lower zone begins at Punta Piedra and extends about 7 km southward to where the lagoon meets the Pacific.

As documented by commercial whaling operations since the 19th century, gray whales begin to occupy the Baja lagoons at the end of each year's boreal autumn. Pregnant females with quickly approaching due dates, or calves born *en route*, arrive in the lagoon first—generally in December and January (Rice and Wolman, 1971). They are followed sequentially by females in estrus, adult males, immature females, and finally by immature males (Herzing and Mate, 1984). Their peak density in LSI is usually reached by mid-February. Visual surveys suggest that adults ("singles") engaging in breeding activities and mothers with older calves occupy the lower and middle zones. Females giving birth and nursing new calves predominantly reside in the upper zone, where the water is warmer and shallower. This distribution has become more pronounced in recent years (González-Carrillo *et al.*, 2006; Swartz *et al.*, 2012).

[a)]Electronic mail: kseger@ucsd.edu

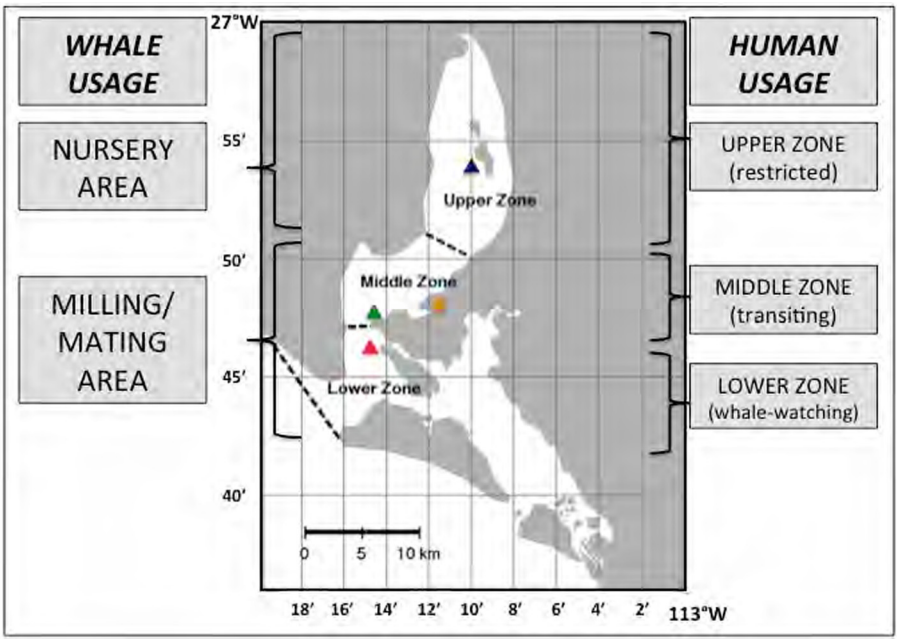

FIG. 1. (Color online) A map of Laguna San Ignacio with dotted lines delineating the three man-made "zones" that divide the lagoon into a relatively heavily trafficked whale-watching zone (lower), a moderately trafficked transit zone (middle) and a restricted nursery (upper). The middle zone has been the only one monitored consistently since 2008. Triangles denote acoustic recorder deployments, while the circle denotes the weather station deployment location.

LSI is a United Nations Educational, Scientific and Cultural Organization site within Mexico's Vizcaino Biosphere Reserve, and is also one of Mexico's federally designated marine protected areas and whale refuges. Local residents have fished the lagoon for over a century, and fishing remains the dominant human activity during whale-watching's off-season, but whale-watching tourism during the breeding season has become increasingly important to the local economy. Eco-tourism charter boats from San Diego began entering LSI in the 1970s to whale-watch during the winter, and in 1984 eco-tourism groups began setting up temporary winter camps along its southern shore (Swartz, 2014). Today the middle zone contains five eco-tourism spots: Camp Kuyima, Kuyimita, Campo Cortez, Baja Expeditions, and Baja Discovery. The upper zone contains only Pachico Whalewatching.

Pangas, which are rigid-hull outboard motor boats with a 12-passenger capacity, are used for transporting tourists from these camps in the middle zone to whale-watch in the lower zone whenever winds are calm enough. Once in the lower zone, the tourist pangas are permitted to approach and observe whales. Also, small (100 ton) cruise ships from San Diego, CA, anchor in the lower zone, and local pangas take their passengers whale-watching in the lower zone. Tourism activity is regulated in terms of the number of pangas allowed in the lower zone at a given time; however, the expected completion of a paved road to the lagoon over the next couple of years is expected to lead to a boost in visitors and an incentive to increase the number of panga trips into the lagoon. Before this study, no information existed on the current ambient acoustic environment of the lagoon. It is difficult to anticipate how potential increases in tourist traffic might affect the ambient acoustic environment without knowing the degree to which it currently contributes.

This paper presents a multi-year analysis of the ambient acoustic environment of all three zones in LSI. The results tackled the following goals: (1) identifying sound sources in the lagoon, (2) determining whether any of these sources are inherently cyclical, (3) identifying the dominant source in each zone, and (4) determining the contribution of anthropogenic noise to the overall ambient noise environment. The rest of the Introduction reviews previous acoustic research in LSI, while Sec. II describes the acoustic instruments used for this study and outlines the methods for deploying and recovering them. Section III explains the analysis methods for comparing ambient acoustic environments on daily, seasonal, and annual bases, using power spectral density percentiles. This analysis approach has been applied in other waterways (Erbe *et al.*, 2013; Merchant *et al.*, 2013), but to our knowledge not to lagoon environments. Section IV presents comparisons of these diel, seasonal, and annual cycles in all three zones, but specifically focuses on data from 2009 and 2011 (when at least two zones were monitored simultaneously). Finally, Sec. V uses the observed patterns to discuss the degree to which panga noise contributes to the overall environment (relative to biological and physical processes). As the amount of tourist activity in LSI has remained relatively stable since 2008 in all three zones, the results of this paper can provide a baseline for comparing any modifications that future increases in tourism activity may create.

B. Previous acoustic research

As part of larger field studies by Mary Lou Jones and Steven Swartz, Marilyn Dahlheim conducted the first acoustic research in LSI at Punta Piedra (middle zone) during the 1980s (Dahlheim *et al.*, 1984; Dahlheim, 1987). In addition to over-the-side audio tape recordings and playback studies starting in 1981, Dahlheim deployed a cabled hydrophone 8 m deep to measure the overall acoustic environment between 1982 and 1984. Dahlheim (1987) also compared gray whale calling rates throughout their migration routes and concluded that the most active calling occurs in their mating/calving grounds (such as LSI). She also conducted measurements of the ambient noise background and found a noise minimum

near 300 Hz. She speculated that gray whales use vocalizations near 300 Hz to take advantage of this acoustic bandwidth "window" below the broadband snapping shrimp cacophony and above croaker and other pulsive biologic sounds at lower frequencies (e.g., near 100 Hz).

Later, Sheyna Wisdom conducted boat-based measurements in 1999 and 2000 (Wisdom, 2000) to study the developmental process of sound production in gray whales. She identified a new call type (type 1a) that tends to precede calves breaching, and associated higher calling rates with increased physical activity (rubbing and swimming compared to resting). Ponce *et al.* (2012) calculated calling rates of the three most common call types–rates that we will use later to consider how much gray whale vocalizations contribute to LSI's ambient acoustic environment.

These researchers have collectively established that gray whales in LSI use at least six call types, ranging from rapid, rhythmic pulses to FM sweeps between 100 and 1600 Hz (Ponce *et al.*, 2012), which are consistent with recordings of gray whales from habitats beyond Laguna San Ignacio (Fish, 1964; Moore and Ljungblad, 1984; Crane and Lashkari, 1996; Ollervides and Rorhkasse, 2007; Stafford *et al.*, 2007). Call functions are believed to include behavioral-state broadcasts (Crane and Lashkari, 1996), contact calling (Fish *et al.*, 1974; Norris *et al.*, 1977) and/or species recognition (Dahlheim *et al.*, 1984). Since these calls lie within the same bandwidth as sounds produced by pangas and tourist fishing vessels, there are conservation and management interests in understanding the relative contributions of vessel noise and gray whales to the acoustic environments.

Other resident sound-producing species include snapping shrimp–either *Crangon dentipes* or *Synalpheus lockingtoni* (Everest *et al.*, 1948; Dahlheim *et al.*, 1984) and croaker fish (D'Spain and Batchelor, 2006; Aalbers and Drawbridge, 2008; Luczkovich *et al.*, 2008). Snapping shrimp sounds fall within a 500 to >3000 kHz bandwidth and they exhibit crepuscular cycles in other tropical waters (Lammers *et al.*, 2008). Winds and tides also play a role in creating background noise levels, but generally at higher frequencies (e.g., above a kilohertz) (Urick, 1983).

II. METHODS

A. Acoustic recording equipment

Since 2008 researchers from the Scripps Institution of Oceanography have collected acoustic data in all three zones (Fig. 1), though rarely from multiple zones in the same season. The same bottom-mounted recorders described in Ponce *et al.* (2012) collected data. Sampling rates were either 6.125 or 12.5 kHz, depending upon the year, and the data were sampled continuously, except for a few hours every 2 days, when data were written to a hard disk. HTI-96-MIN (High Tech Inc.) hydrophones with −171 dB re 1 V/μPa sensitivity were used for all six years.

B. Field procedures

Acoustic recorders were deployed each season in early February and recovered in mid-March. They were attached to a 100 m polypropylene line connected on each end to an anchor. Depending upon the year, one, two, or three recorders were attached to each line, and these sets of recorders will be referred to as "assemblies." Each assembly was hand-lowered from the side of a slow-moving panga so it could be laid out horizontally along the lagoon's bottom. Because polypropylene is buoyant, it could potentially entangle whales, so small lead fishing weights were attached every 5 m to hold the line close to the bottom. While this configuration reduced entanglement risk, it increased the potential that an assembly would be buried. To recover an assembly, a grappling hook was towed from the stern of a slow-moving panga to snag the polypropylene line and manually reel it in.

Specific deployment locations of acoustic assemblies within a zone will henceforth be referred to as "sites." Instruments were deployed at specific sites within each of the three zones. The site in the middle zone (near Punta Piedra) is the same location as in Dahlheim's 1980s research (Dahlheim *et al.*, 1984; Dahlheim, 1987). Single, double, or six-recorder assemblies have occupied this site continuously since 2008. Single- or double-recorder assemblies have been deployed between 2009 and 2012 at a site in the lower zone. A single-recorder assembly was deployed near Isla Pelicanos in the upper zone during 2009 and 2011. Table I summarizes recording dates, bottom depths, and GPS coordinates of all deployments.

A weather station was set up all years except 2013 to supplement acoustic recordings with wind (30-s sampling rate), temperature, and rainfall data. The "HOBOware" autonomous weather station was mounted on a 5 m wooden pole, near the Baja Discovery ecotourism camp on Punta Piedra.

III. DATA ANALYSIS

A. Acoustic data processing

Acoustic analyses for every site over all years began by downloading the raw binary acoustic data, converting them into pressure units, and correcting the frequency spectrum

TABLE I. A listing of the time frames, depths, and locations of all autonomous acoustic recorders (units) analyzed in this report.

Year	Lower Zone: lat. 26°47.136′, long. −113°15.134′; # of recorders; date; depth	Middle Zone: lat. 26°47.658′, long. −113°14.645′; # of recorders; date; depth	Upper Zone: lat. 26°53.664′, long. −113°10.948′; # of recorders; date; depth
2008	0 recorders	1 recorder; February 9 to March 8; 13 m	0 recorders
2009	0 recorders	2 recorders; February 13 to March 22; 11 m	1 recorder; February 15 to March 12; 5 m
2010	1 recorder; February 6 to March 4; 5 m	6 recorders; February 6 to March 4; 10 m	0 recorders
2011	2 recorders; February 5 to March 10; depths not recorded	2 recorders; February 5 to March 7; 12 m	1 recorder; February 6 to March 9; 5 m
2012	1 recorder; February 11 to March 10; 20 m	2 recorders; February 11 to March 10; 11 m	0 recorders
2013	0 recorders	1 recorder; February 18 to March 6; 12 m	0 recorders

for frequency-dependent hydrophone sensitivities. Then power spectral densities (PSDs) were computed in dB re 1 μPa^2/Hz and estimated to 3-Hz resolution each minute, by averaging FFT snapshots (overlapped 50%) over 1 min intervals. Data below 200 Hz were excluded because this frequency band lies outside the range of most gray whale calls and was often contaminated by flow noise and noise from the recorders rolling along the bottom.

These PSD time samples were then processed in three different ways. The first approach defined two bandwidths of biological relevance: 500–3120 Hz (the snapping shrimp band) and 200–500 Hz (the non-snapping shrimp band). The time-averaged PSD was integrated over each of these two bandwidths to produce an average sound pressure level (SPL) in terms of dB re 1 μPa for every minute. The 1st, 10th–90th (in tenths), and 99th percentile distributions of these SPL estimates were then generated every hour. As a result, a given percentile could be plotted against time with hourly resolution for all instruments in all zones for all years. This allowed both cyclical (fluctuating on a regular basis) and secular (long-term, non-cyclical) changes to be spotted. The 10th, 90th, and 99th percentiles were found to be particularly useful in that they were found to represent diffuse background noise levels (10th) and relatively extreme (intense) transient events (90th and 99th).

The second approach to analyzing the ambient noise background involved searching for diel cycles. A given SPL percentile would be averaged across all days at a specific time of day. For example, all SPL values from the 99th percentile computed between 0100 and 0200 from each day of a given deployment would be averaged together, with identical analysis repeated for each subsequent hour of the day. Plots of these averaged percentiles as a function of the hour-of-day were examined for potential diel cycles.

Finally, the estimated PSD percentiles were also computed for every frequency bin across time—an approach that permitted an entire deployment record to be displayed as a set of frequency-dependent PSD percentile curves. Whenever multiple recorders were deployed together as an assembly, their seasonal PSD percentiles were compared, but data are presented here for select years and zones from a single recorder in each assembly.

B. Identifying potential source mechanisms

Cyclical patterns in the acoustic data were reflected in the diel plots and used to infer likely mechanisms behind the ambient noise field. Whenever pangas, snapping shrimp, or fish were postulated to be likely contributors, 2-min long spectrograms were manually reviewed during times of high and low noise intensity to flag the presence of these distinctive signals. Ten of the hours in the data when SPL levels were both lowest and highest were selected, and each of these 20 hour-long spectrogram were reviewed. For the specific case of pangas, the number of transits was counted, and the SPL of each transit was noted. These levels were compared to various SPL percentiles to ensure that pangas were truly the driving source mechanism behind these cycles.

Simultaneous measurements from the weather station also aided in identifying possible driving mechanisms. For example, Pearson's correlation coefficients were computed between wind speed time series collected at Punta Piedra and sound intensities recorded from the middle zone.

IV. RESULTS

Data from one recorder at each site for 2008 through 2013 are presented here, including results from 2009 and 2011 in the upper zone, all six years in the middle zone, and 2011 in the lower zone. There was considerable variation in spectral levels below 200 Hz from recorders spaced only a few meters apart. This was likely due to varying levels of silt burial and plants and gravel colliding with the recorder during heavy tidal flows, so analysis was restricted to frequencies above 200 Hz.

The results are arranged by increasingly longer timescales: (a) short-term diel patterns, (b) seasonal patterns within and between zones, and (c) multi-year characteristics. The year 2011 will be used as a "reference" year, as it was the one season where all three zones were monitored simultaneously. Figure 2 shows sample spectrograms of the various source mechanisms in LSI.

A. General observations

Figure 3 displays examples of 4-day time series (February 25–29, 2011) of SPL between 200 and 500 Hz and 500–3120 Hz in all three zones. Over the 500–3120 Hz band, the upper zone's median levels (118 dB re 1 μPa) were more intense than both the middle (110 dB re 1 μPa) and lower zone's (103 dB re 1 μPa) median levels. By contrast, in the 200–500 Hz band, the upper zone's median levels (99 dB re 1 μPa) were only slightly higher than both the middle (95 dB re 1 μPa) and the lower zone's (96 dB re 1 μPa) median levels. As will be shown later, these differences arise from higher snapping shrimp activity in the upper zone.

Over the 500–3120 Hz band, the maximum spread between the 99th and 1st percentiles (dash-dotted lines) in the upper zone was 9 dB, versus a 13 dB spread in the middle zone and a 17 dB spread in the lower zone. Over the 200–500 Hz band, the upper zone's spread was 12 dB, versus a 28 dB spread in the middle zone and a 34 dB spread in the lower zone. The relatively smaller spreads in the upper zone indicate that it is the most stationary acoustic environment, even though it is the most acoustically intense ("noisy") zone above 500 Hz.

One feature in the lower and middle zones, but not in the upper zone, is a daily waxing and waning of the 1st to 99th percentile spreads. The middle zone's percentile spread is greatest in the higher frequency band (500–3120 Hz) during daytime hours: usually between 08:00 and 15:00. The lower zone's 1st to 99th percentile spread peaks rapidly during evening hours [Figs. 3(c) and 3(f)]. Section IV C examines these potential cyclical patterns more rigorously.

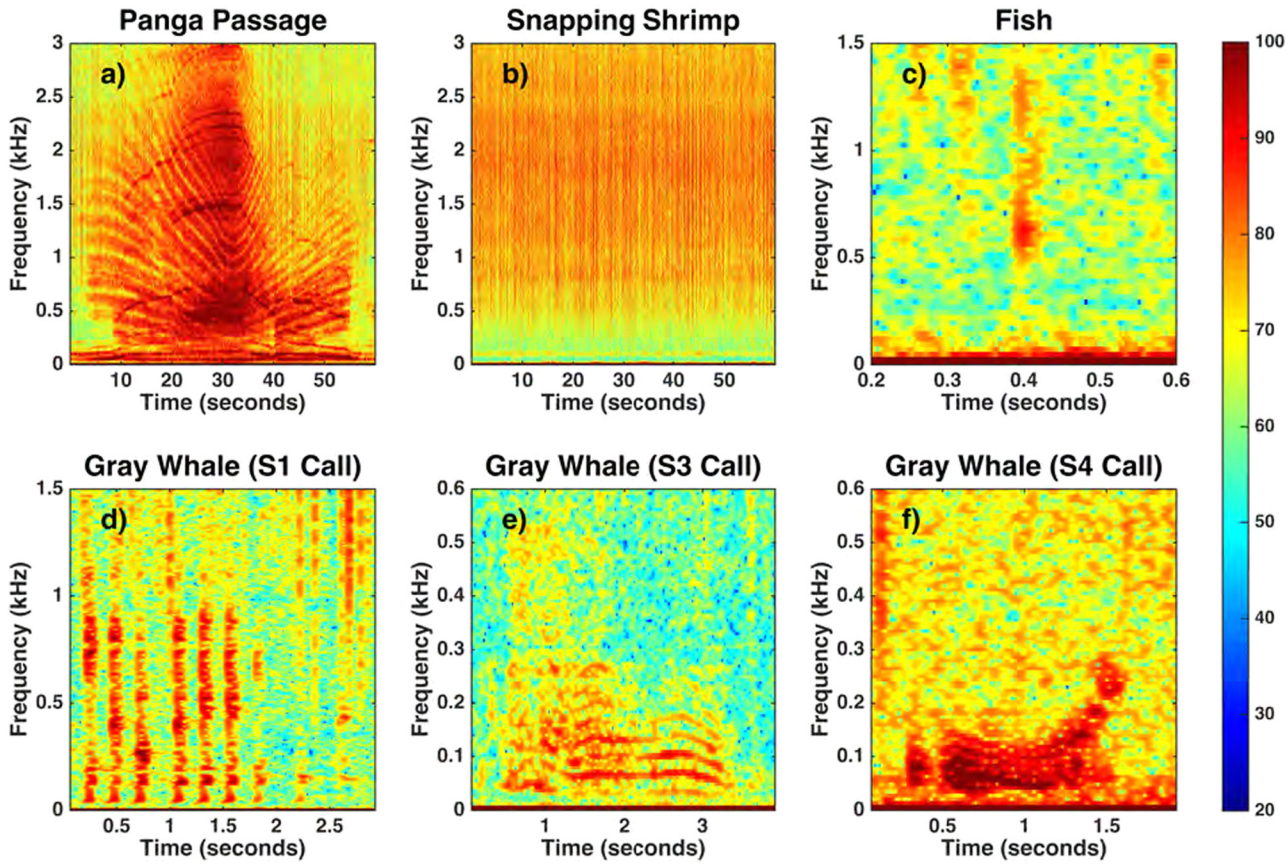

FIG. 2. (Color online) Sound sources in Laguna San Ignacio are physical, biological, and man-made. Non-cetacean examples from 2010 and 2011 are (a) panga engines; (b) snapping shrimp; and (c) fish (most likely croaker). Gray whale calls include pulsive sounds like (d) "S1," and frequency modulated sounds like (e) "S3" and (f) "S4." The sampling rate for all examples was 12.5 kHz. Spectrograms were generated with a Hanning window and used sampling windows ranging from 512 to 2048 points, all with 90% overlap.

B. Diel cycles in all three zones

The initial impressions of cyclical activity in Fig. 3(b) and 3(c) are confirmed by Fig. 4, which displays the percentiles of averaged SPLs across both frequency bands for all three zones in 2011. Three distinct cycles can be seen. The first is a slight crepuscular (dawn/dusk activity) cycle visible in all zones across most bandwidths. For example, Fig. 4(a) shows these crepuscular peaks occur over the 500–3120 Hz bandwidth in the 10th percentile—a pattern consistent with crepuscular cycles exhibited by snapping shrimp in Hawaiian waters (Lammers *et al.*, 2008).

This crepuscular cycle is superseded by other cycles in the middle and lower zones. In the middle zone, a distinct daily cycle of extreme events [the 90th and 99th percentiles; Figs. 4(c) and 4(d)] peaks at midday in the lower frequency band. Midday is when pangas return to the land-based camps for lunch break, and review of the raw acoustic data confirmed that numerous panga signatures exist at similar SPLs to those shown in Figs. 4(c) and 4(d).

Of particular note in the lower zone is the 99th percentile [Fig. 4(d)], when the lower frequency band has bimodal peaks near 10:00 and 18:00, and a local minimum at 13:00. These times coincide with typical daily panga activity in the lagoon. For example, the 10:00 h experiences high whale-watching traffic in the lower zone, whereas around 13:00 pangas return to the camps for lunch. Randomly selected samples of the raw acoustic data around 10:00 again confirmed panga activity.

The lower zone's peak in the 99th percentile between 200 and 500 Hz in Fig. 4(d), which occurs at 18:00, must arise from a different source mechanism than pangas, since most vessels are moored by dusk. Across nearly all percentiles, the background noise SPL increases by 10 dB in just a few hours. Inspection of raw data confirmed that these peaks arise from fish (croaker spp.). As all percentiles are affected, this suggests that the drumming fish dominate the acoustic environment at least 90% of the time (e.g., 54 min per hour) during the early evening hours. While the maximum is centered at 18:00, shifting sunset times across the season has diffused the diel peaks in Fig. 4.

Figure 5 provides 3-min snapshots of spectrograms from a single day that confirm many of the observations of Fig. 4. One sees how the upper zone noise levels are the most intense and the least variable of the zones, and that the noon and midnight hours in the upper zone are indeed "quieter" than sunrise and sunset hours. The upper zone also displays higher SPLs across the snapping shrimp bandwidth than the middle zone, giving credence that these small crustaceans are the driving source mechanism shaping the upper zone's acoustic environment. Finally, Fig. 5(g) illustrates a panga transit in the lower zone during the first 40 s.

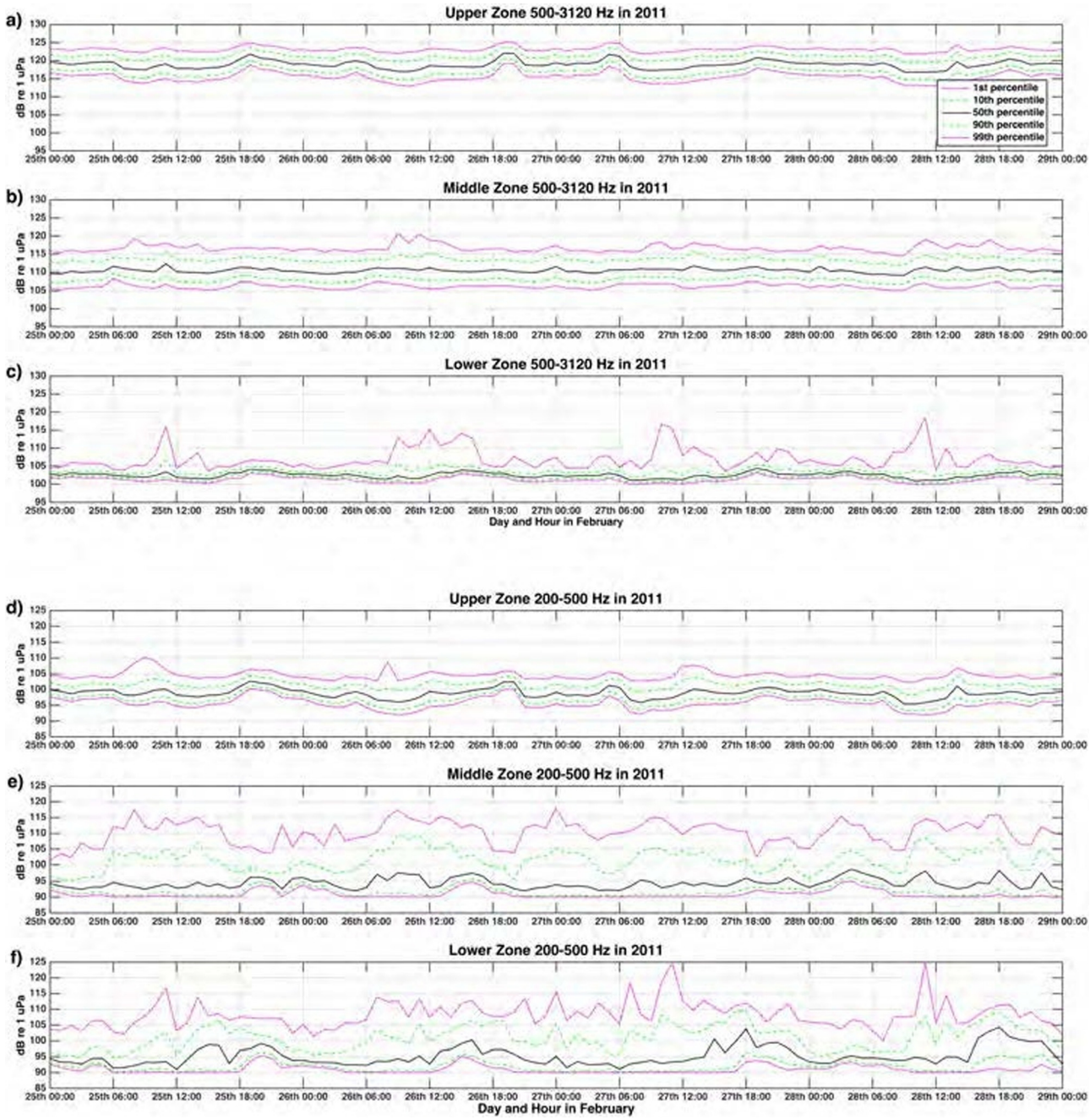

FIG. 3. (Color online) The 1st (dash-dotted), 10th (dashed), median (solid), 19th (dashed), and 99th (dash-dotted) percentiles of intensity (dB re 1 μPa) calculated hourly across 4 days for the (a)–(c) 500–3120 Hz and (d)–(f) 200–500 Hz bandwidths at the (a) and (c) upper, (b) and (e) middle, and (c) and (f) lower zones.

C. "Seasonality" across all three zones

A "season" is defined here as the 2 months each year when acoustic data were collected. Therefore, "seasonality" in the zones will explore trends in the acoustic environment that existed over the couple months when gray whales occupy Laguna San Ignacio. Figure 6, which is a time expansion of Fig. 3, shows that the upper zone still displays the most intense yet least variable noise levels. The strong croaker chorusing peaks in the lower zone and the midday peaks in the middle zone that were rather obvious in Fig. 3 can still be spotted upon close inspection in Fig. 6. From this larger "bird's eye view"; however, the croaker chorusing seems modulated by a 2-week cycle that is most pronounced in the median levels of the lower zone. While their activity could be related to the lunar phase, the restricted deployment time of 45 days prevents verification of this idea.

In addition to lunar phase, wind speed is a natural phenomenon that could be related to noise levels. The median values of measured wind speed (raw data sample rate = 30 s; from the HOBOware weather station at Punta Piedra; medians calculated every hour) were compared against hourly 50th percentile sound levels between both the 200–500 Hz and 500–3120 Hz bandwidths from the middle zone. Comparisons were time-lagged by shifting sound level response to wind speed from 0 to 24 hours. The maximum

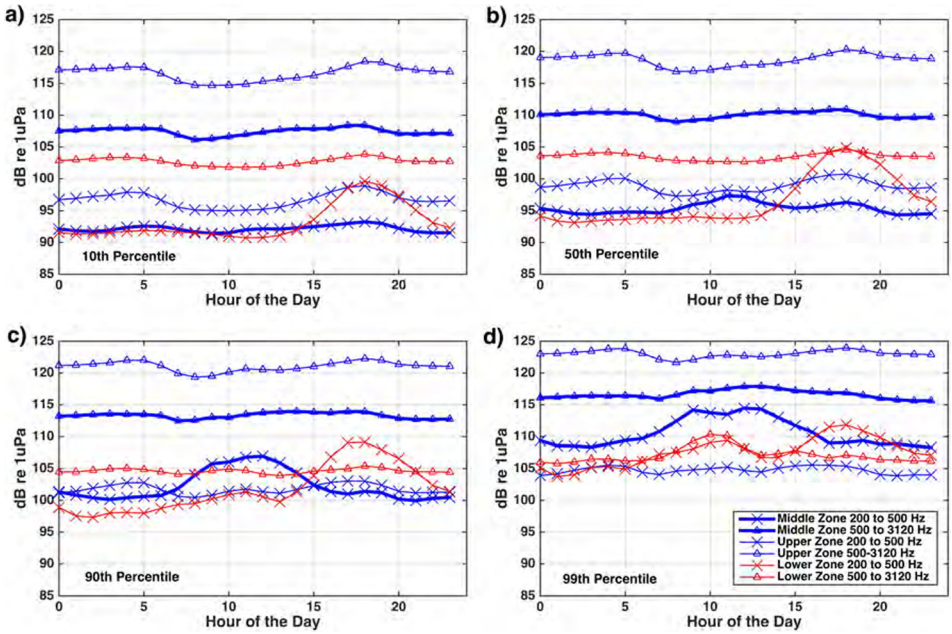

FIG. 4. (Color online) The average percentile intensity across each hour of the day during 2011 is presented for four percentiles across 200–500 Hz (× marker) and 500–3120 Hz (triangle marker), for the middle, upper, and lower zones of Laguna San Ignacio. The (a) 10th, (b) 50th, (c) 90th, and (d) 99th percentiles of hourly samples are shown.

Pearson's correlation coefficient with any significant statistical comparison (p value = 0.05) was −0.12. We thus conclude that wind was not a driving source mechanism for the 50th percentile of sound level in the middle zone's acoustic environment below 3 kHz.

Figures 7 and 8 plot the percentile distributions of the PSD for all three zones during 2011. An example interpretation of these figures is that the PSD at 2 kHz in the middle zone (black lines) is at or below 85 dB re 1 μPa^2/Hz during 99% (thickest line) of the season. Similarly, the PSD at 2 kHz in the upper zone is at or below 92 dB re 1 μPa^2/Hz for 99% of the season.

Above 700 Hz, the upper zone has sound levels 8–12 dB higher than the middle zone for all percentiles. Below 700 Hz, however, the middle zone begins to have higher sound levels (Fig. 7, grey arrow). The largest difference (15 dB) lies in the 99th percentile across the 200–300 Hz bandwidth (Fig. 7, dashed arrow). The lower zone displays similar PSD values in Fig. 8, and its PSD spectrum is more closely related to the middle zone than to the upper zone. The largest swings in PSD (a 20–40 dB separation between 10th and 90th percentiles denoted by the gray arrow in Fig. 8) occur below 500 Hz in the lower zone and will be discussed further in Sec. IV D.

Figure 8 also shows that the lower zone has a 300 Hz sound minimum in the 10th and 50th percentiles, but it shifts to a 1000 Hz sound minimum in the 90th and 99th percentiles. Thus, loud transient sound sources tend to have lower-frequency components than the diffuse noise–a characteristic of panga transits. The upper zone seems to have no sound minimum with respect to frequency–the apparent minimum in the 99th percentile falls too closely to 200 Hz to rule out flow noise contamination.

When comparing daytime versus nighttime PSDs [Fig. 7(b) and 7(c)], the middle and upper zones in 2011 have a negligible difference in daytime and nighttime sound levels. However, the lower zone, at the 90th (dashed line) and 99th (thick line) percentiles, has a nighttime with higher sound levels below 500 Hz, but a daytime with higher sound levels between 500 and 1000 Hz [Fig. 8(b)]. Daytime vs nighttime comparisons were split at 6 pm and 6 am–times of rapid changes in ambient noise levels in the lower zone. Thus, Fig. 8(c) displays dusk-centered and dawn-centered PSDs to avoid splitting sound level measurements during times of high fluctuation. As a result, sound levels from noon to midnight (dusk) were higher than from midnight to noon (dawn) for extreme events across nearly all frequencies, consistent with the timing of croaker activity [Fig. 8(c), grey circle].

D. A 2-year comparison in the middle and upper zones

The year 2009 was the only other year that data were simultaneously recorded in both the upper and middle zones. Figures 9 and 10 present the 2009 results in the same manner as Figs. 4 and 7 did for 2011.

The upper zone's diel patterns in 2009 are similar to those of 2011. One very minor difference is that, in 2011, a very small peak in the 90th and 99th percentiles at the 10:00 h [Fig. 4(c) and 4(d)] did not exist at all in 2009 [Fig. 9(c) and 9(d)]. A very small amount of panga traffic exists in the upper zone, and may have been less in 2009 than in 2011, but no records are available to verify this. The middle zone percentiles in 2009 were consistently 5 dB higher than 2011 for both frequency bands throughout the day. Also, Figs. 9(c) and 9(d) show that the panga-related peaks at the 90th and 99th percentiles were more pronounced in 2009 than in 2011–below 1000 Hz; daytime hours are as much as 10 dB higher than during the night. (Recall that 2011 had daytime sound levels only 1–2 dB higher than nighttime sound levels.) This contrast exits not because the daytime hours in 2009 were so much "louder," but because the nighttime hours in 2009 were so much "quieter" (compare thick Xed lines in Figs. 4(c) and 4(d) to those in Figs. 9(c) and 9(d). According to Fig. 10(a), the 300 Hz minimum was more obvious in 2009 than in 2011. However, below 800 Hz, the 99th percentile PSD in 2009 is nearly 14 dB lower than in 2011.

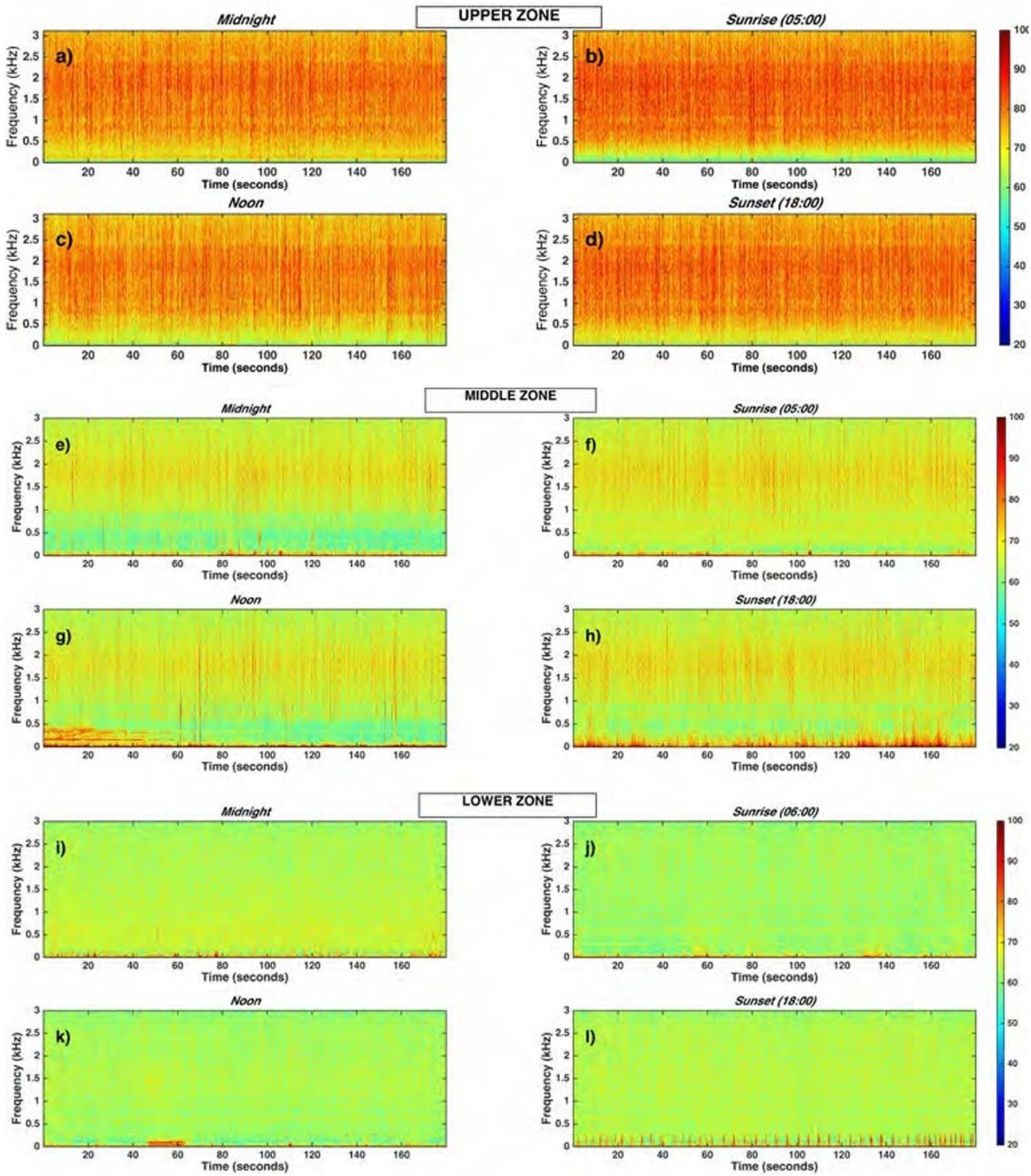

FIG. 5. (Color online) Typical snapshots of the ambient noise environment in the (a)–(d) upper zone as compared to the (e)–(h) middle zone and (i)–(l) lower zone. The four snapshots in time are (a), (e), and (i) midnight, (b), (f), and (j) sunrise, (c), (g), and (k) noon, and (d), (h), and (l) sunset. All spectrograms were generated using a 1024 FFT size with 90% overlap.

The statistical results presented here are consistent with spot-checks of the acoustic data. For example, ten random perusals of raw data at 18:00 in the lower zone [i.e., the center of the hourly averaged peak from Figs. 4(a)–4(c)] showed that panga activity never existed, but the drumming of croaker fish was consistently high. At the same times in the middle and upper zone data, relatively moderate and low croaker activity existed. These results are consistent with current understandings of croaker activity whereby the fish tend to inhabit shallow waters in silty areas very close to the entrances of Baja coastal lagoons (Fish, 1964; Fish and Mawbray, 1970; Johnson, 1948; Batchelor, 2015).

E. Multi-year comparisons for the middle zone

Between 2008 and 2013, the same recorder (Unit 2) was deployed in the middle zone every year except 2010. In 2010 Unit 2 was more deeply buried than the other

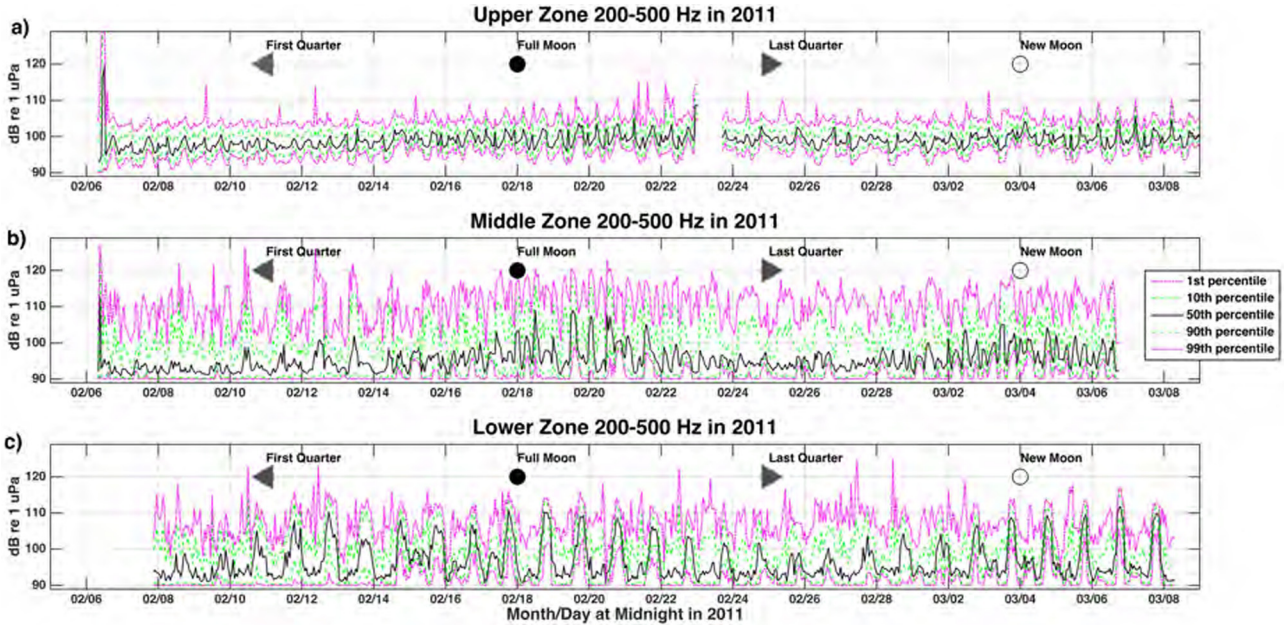

FIG. 6. (Color online) This is an expansion of Fig. 3 to the entire 2011 deployment, but only for the lower frequency band (200–500 Hz). SPL averaged across 1-h bins is shown for the (a) upper zone, (b) middle zone, and (c) lower zone. Black (new), gray (quarter), and white (full) circles denote lunar phases.

recorders, but a different unit (same design and calibration) recorded a less contaminated dataset. Thus, a multi-year comparison of this acoustic environment is feasible.

Figure 11 shows that the overall ambient noise environment was stable across all six years, although the first 3 years (2008–2010) have less intense PSD levels than the next 3 years (2011–2013). The greatest difference in PSD levels between 2008 and 2013 was 12 dB, which occurred at 450 Hz at the 90th percentile between 2011 and 2013. A review of the acoustic data confirmed that recorder motion on the ocean floor does tend to contaminate frequencies below 200 Hz, explaining the wide variations observed over this frequency range. The noise minimum at 300 Hz found in 2009 and 2011 persists across all 6 years in the middle zone, supporting the observations of Dahlheim (1987) that gray whales (whose vocalizations center around 300 Hz) tend to call where noise from snapping shrimp and boat engines is

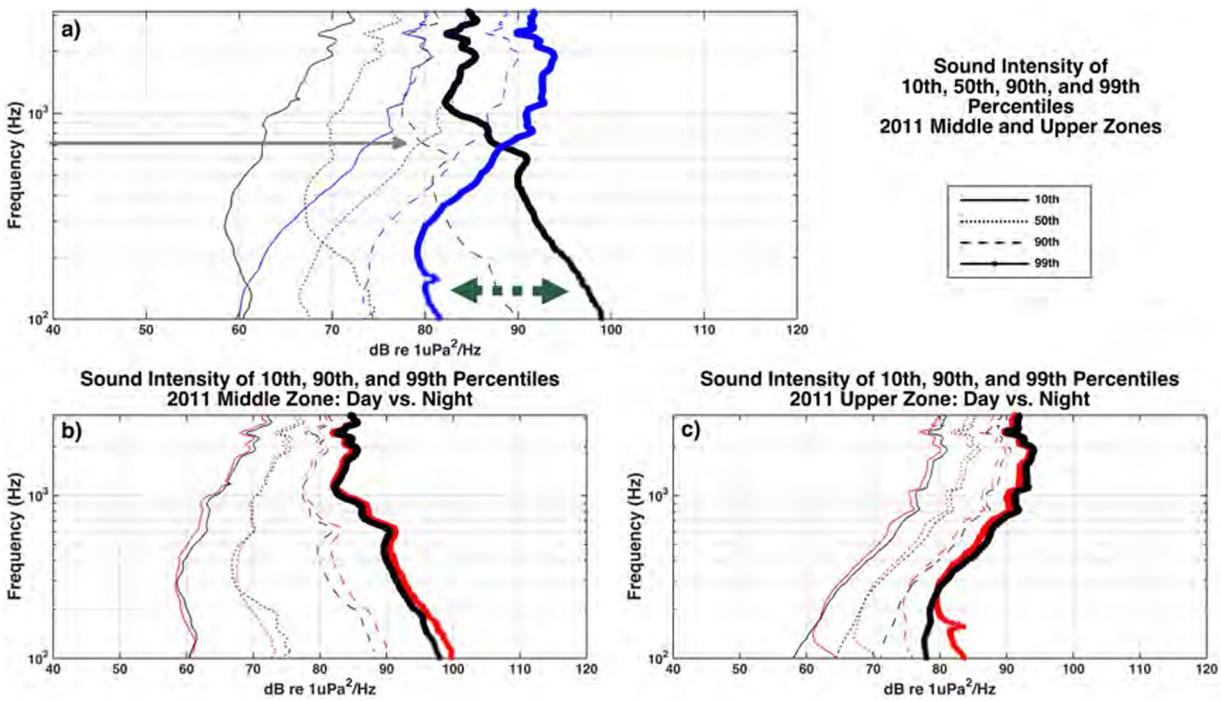

FIG. 7. (Color online) Contour lines for the 10th (solid), 50th (dotted), 90th (dashed), and 99th (thick) percentiles compare these four power spectral densities on a logarithmic scale between 100 and 3125 Hz in the middle (dark shaded) and upper (light shaded) zones in the lagoon for 2011. (a) shows sound intensity across 24 h. (b) and (c) divide sound intensity between night (1800–0600) in a dark shade and day (0600–1800) in a gray shade for the middle (left) and upper (right) zones.

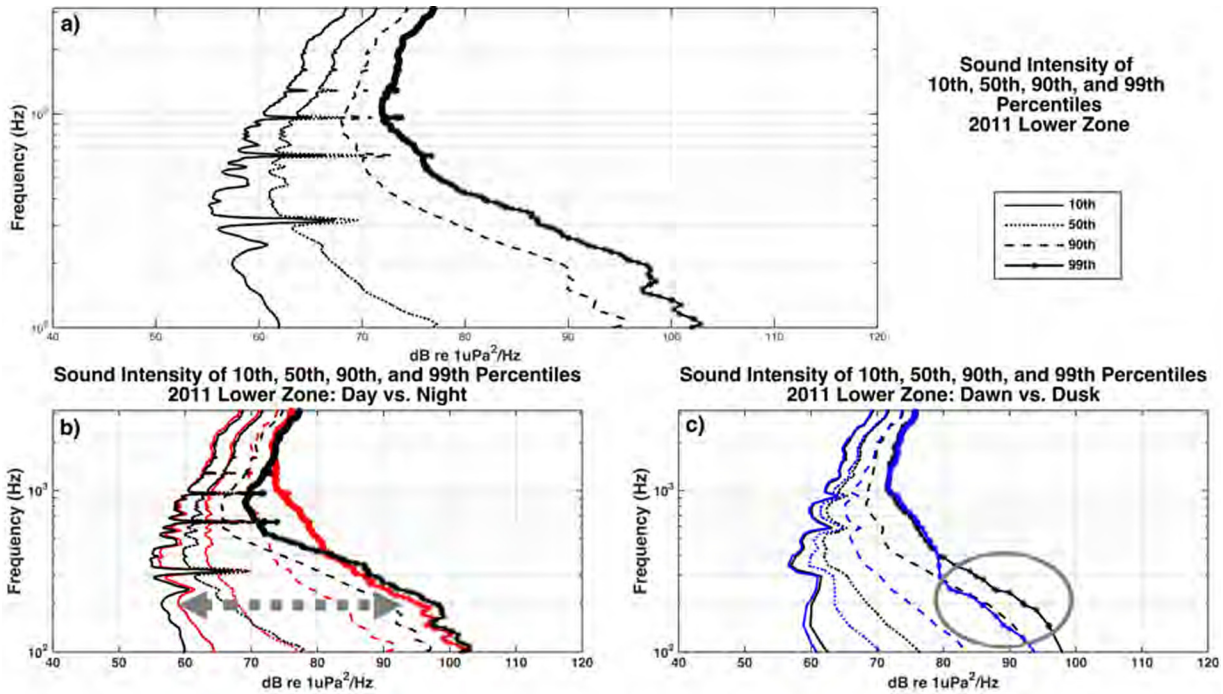

FIG. 8. (Color online) Same as Fig. 7, but data for the lower zone are plotted. A dawn vs dusk comparison has been added, however, to show the impact of the croaker chorusing. Dusk covers noon to midnight and is shown in the dark shade; dawn covers midnight to noon and is shown in the gray shade.

least prevalent. Thus, the 300 Hz acoustic minimum in the middle zone of LSI has been consistent for nearly 25 years.

V. DISCUSSION

The main motivations of this paper were to investigate the underwater ambient noise environment of a World Heritage site where the last acoustic research is from over 20 years ago, and to determine the extent of noise contributions from panga traffic. Other research in whale-watching waters, particularly in Puget Sound, identifies noise from vessels as a key threat in the recovery and survival of southwest resident killer whales (Holt, 2008). Currently, LSI is a low trafficked area and not comparable to many other highly trafficked whale-watching locations, but that may change if tourism grows in the future. Therefore, it is important to identify baseline sound sources and their relative contributions to the acoustic environments now. Both power spectral densities and SPL percentiles were analyzed. This is a relatively recent approach that has been applied to a strait, a

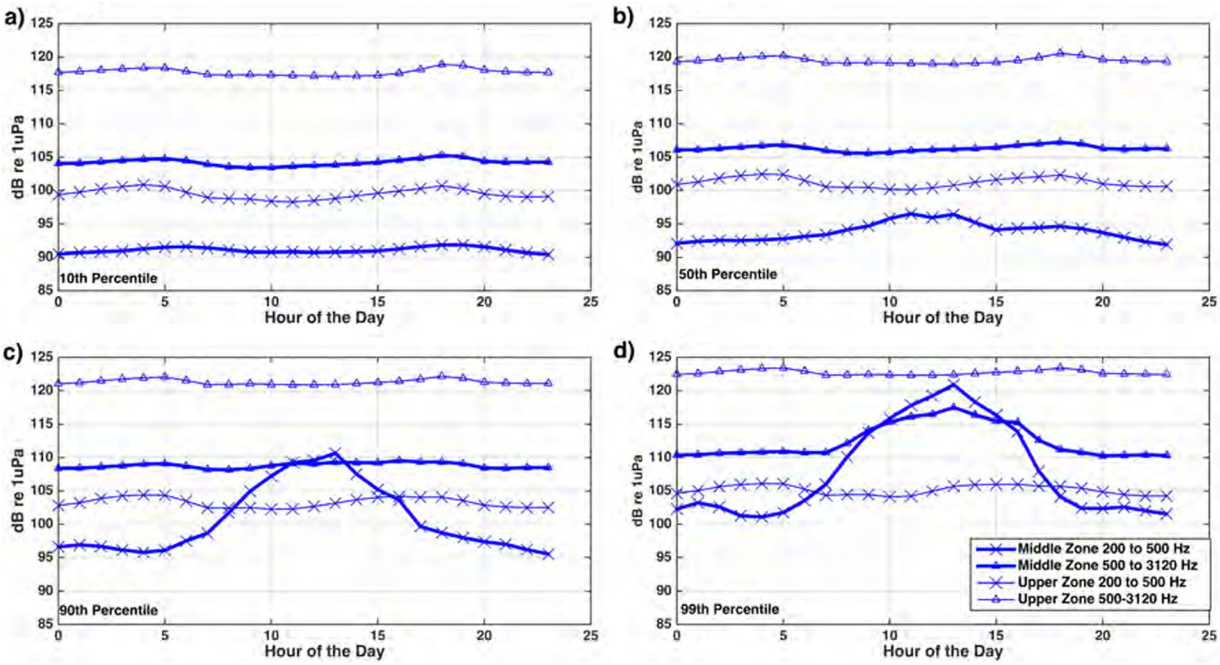

FIG. 9. (Color online) Same as Fig. 4, but with data plotted for 2009.

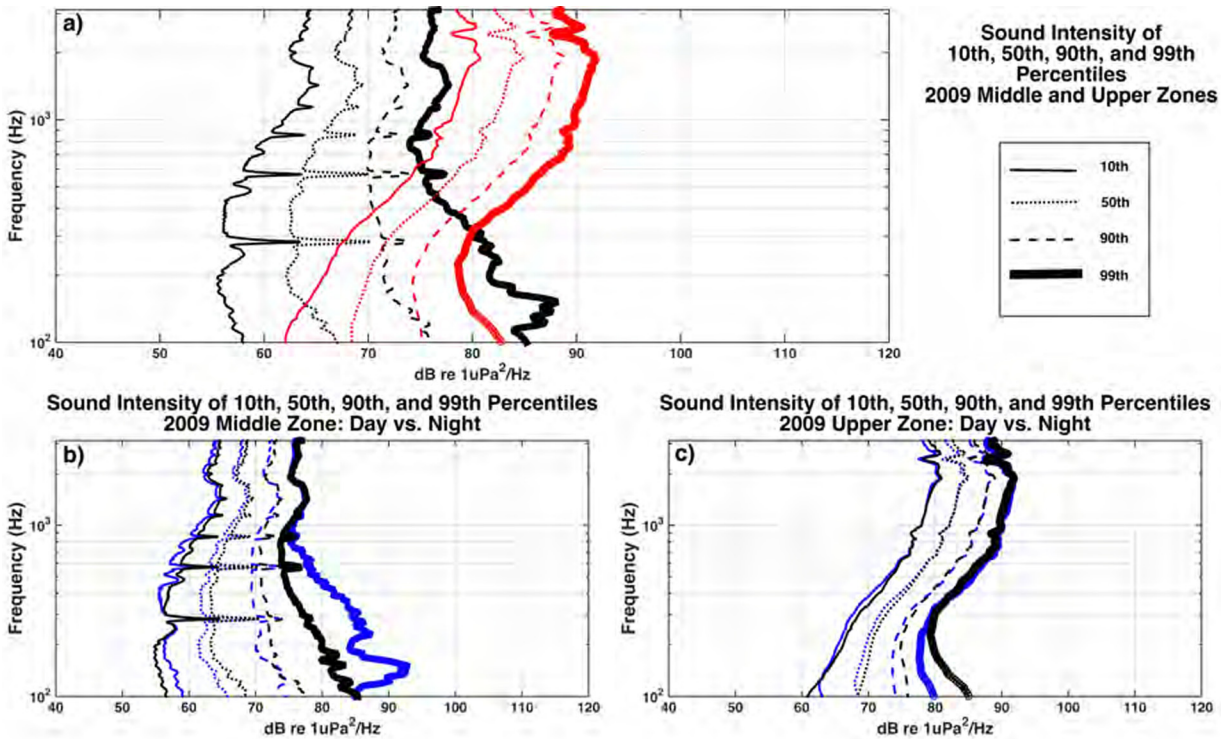

FIG. 10. (Color online) Same as Fig. 7, but with data plotted for 2009.

continental shelf, and a firth (Erbe *et al.*, 2013; Merchant *et al.*, 2013), but not to a subtropical lagoon.

Sound sources in LSI that could be identified using diel cycle analysis included snapping shrimp, panga transits, and croaker vocalizations. Common physical source mechanisms were also examined, but wind speed did not associate as closely with sound levels as did biological and anthropogenic sources; for example, croaker and snapping shrimp activity generated the largest diel patterns in the data.

To confirm that pangas were a source of background noise at the 99th percentiles of the middle and lower zones, panga passes were tabulated in the raw acoustic data from all three zones in 2011. The results suggest that pangas, indeed, make a measurable contribution to ambient noise levels, but only for short and sporadic periods throughout the dataset. In the upper zone, the most intense 99th percentile values were usually concurrent with a single close panga transit or the occasional amount of heavy flow noise. In the middle zone, the most intense 99th percentile values were concurrent with multiple panga transits. In the lower zone, the most intense 99th percentile values concurred sometimes with multiple panga transits, but mostly with high levels of croaker activity.

Interestingly, gray whale calls make a smaller contribution to the bulk ambient acoustic environment than pangas. Their relatively low intensity, as well as their low production rate as established by Ponce *et al.* (2012), provides an explanation for why. Received levels of gray whale calls tend to be less than 145 dB re 1 μPa in our data and from past research (Moore and Ljungblad, 1984; Dahlheim, 1987). Even though these levels are clearly higher than the ambient SPL percentiles shown in Fig. 3, the calls occur relatively infrequently. According to Ponce *et al.* (2012), the call rates of their three most common detected vocalizations were 198 calls/h (S1), 29 calls/h (S4), and 21 calls/h (S3). Considering typical call durations of a second or less, these vocalizations would theoretically be detected only at the 99.5th, 99.993rd, and 99.985th SPL percentiles, respectively. In addition, as

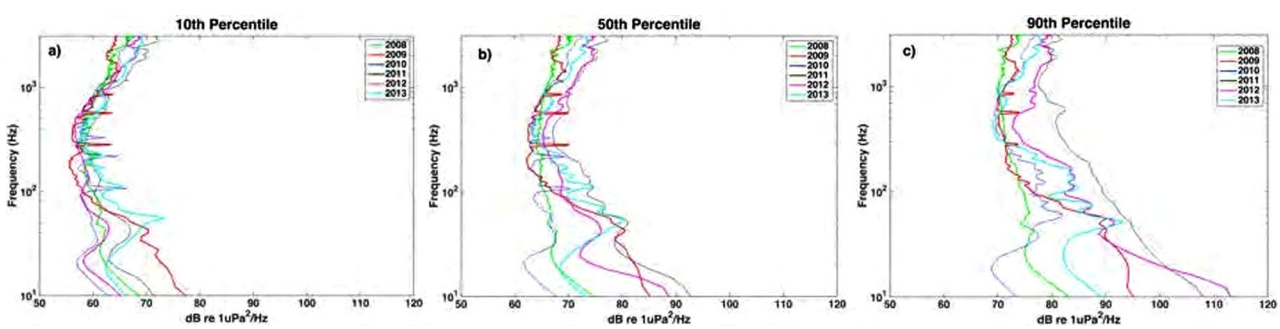

FIG. 11. (Color online) The (a) 10th, (b) 50th, and (c) 90th percentiles for all 6 years between 2008 and 2013 in the middle zone are plotted against each other.

the calls are much shorter than the 1-min averaging window used to estimate the SPL percentiles, their contribution to a 1-min SPL average is relatively miniscule.

Panga transits also leave a relatively minor temporal acoustic footprint in the noise statistics—only the 90th and 99th percentiles exhibit a "lunch-time" effect when pangas are shuttling tourists back to their land-based eco-tourism camps for a meal. Once in awhile, this effect creeps into the 50th percentile. In other words, the acoustic presence of pangas is usually only "felt" for 1 to 6 min each hour (1%–10% of the time) during mid-morning to early afternoon, and rarely "felt" for half of an hour (50% of the time) during other times of the day. Direct comparisons to other whale-watching areas are difficult to make since daily cycles of percentile data are not available. However, vessel activity in Haro Strait, where the Southern resident killer whales inhabit, is comprised of more (and "louder") vessel types that increase SPL during summer days by 5 dB re 1 μPa above summer nights and winter-time. Furthermore, this location already contains nearly constant non-whale-watching vessel noise year round (Holt, 2008).

Often studies of anthropogenic contributions to acoustic environments implicitly assume that undisturbed environments have low noise levels. A contrary situation exists in the upper zone, otherwise known as the "nursery," where the most intense and sustained ambient noise levels are generated by snapping shrimp. The fact that a whale nursery exists in a "loud" environment seems counterintuitive at first. Upon further consideration, however, a constant din might provide protective cover.

To protect a calf from predators and a mother from male harassment, disguising the calf's (and mother's) whereabouts is desirable. The upper zone may provide such protection because it is turbid, which provides visual camouflage. It is also shallow, meaning that a mother who keeps her calf along the shore only has three of the six directions to monitor (i.e., the top, bottom, and coastal sides of the calf are protected while the front, back, and open lagoon sides of the calf are exposed). Along with providing visual camouflage, the upper zone may provide an analogous "aural camouflage" by impeding a predator's ability to hear a calf, or an aggressive male whale's ability to harass a mother. In this relatively loud acoustic environment, snapping shrimp maintain a received level above a 115 dB re 1 μPa level 90% or more of the time, and the lower limits of their bandwidth do overlap with the upper frequencies of gray whale calls. A mother and calf right beside each other would be able to communicate sporadically at low source levels, albeit above the surrounding din, thereby partially masking their calls from predators or aggressive males. While there are no natural predators in the upper zone of LSI, other researchers have proposed that during their migration north, it would be critical for calves and mothers to detect each other's calls over a noisy din, and the upper zone's snapping shrimp cacophony could provide a training area to develop this skill (Perryman and Weller, 2015). Aside from predators, the upper zone could also be an escape from particularly active and / or aggressive conspecifics.

Other explanations exist for why mothers and newborn calves tolerate high noise levels in the upper zone. For example, mother whales may simply prefer the warmer and saltier waters of the upper zone, or may reside there to avoid the aggressive mating behaviors of single animals in the lower and middle zones.

VI. CONCLUSION

The main features in the ambient noise structure across all of LSI's zones can be summarized in a few main points. First, all recorders at a single site collected very similar data above 200 Hz. Below 200 Hz, self-movements of the recorders contaminated the datasets from each recorder differently, so analyses were only performed for bandwidths above 200 Hz.

Second, broadband sound pressure levels are greatest in the upper zone, as compared to relatively moderate levels in the middle zone and lower zone. The least variation (smallest spread between 1st and 99th percentiles) in SPL also exists in the upper zone. We speculate that this consistently "louder" acoustic environment in the upper zone may conveniently provide aural camouflaging for both mothers and young calves.

Third, although snapping shrimp, pangas, croaker fish, gray whales, and wind are all potential sound sources in Laguna San Ignacio, only the first three contribute substantially to at least one portion of the lagoon. Gray whale calls are so intermittent that they are difficult to detect with the percentile methods used in this study, and wind speed did not correlate significantly with SPL at any percentile. Diel cycles are strongly present in panga and croaker activity, and partially so in snapping shrimp activity. Each zone has its own set of distinctive sound-source mechanisms with their own diel cycles. In the upper zone, snapping shrimp dominate higher frequencies and their SPL levels peak crepuscularly. In the middle zone crepuscular snapping shrimp still dominated the higher frequencies, but lunch-time panga transits also generated a diel cycle this is apparent at the 90th percentile level (i.e., present around 6 min per hour at midday). Wind speed does not correlate significantly with median sound levels in the middle zone. In the lower zone the same snapping shrimp contributions are evident, but panga transits that coincide with the morning and afternoon whale-watching time periods contribute to the 99th percentiles. Croaker activity is the dominant source of noise in the lower zone at frequencies below 1500 Hz during a sunset-centered cycle.

Fourth, noise from panga transits, although relatively rare, contributes more to the ambient noise environment than gray whale calls. The noise contribution from pangas is most prominent in the middle zone above the 90th percentile during the day. On the basis of the day/night PSD comparisons from Fig. 9, pangas impact the frequency band between 300 and 1000 Hz. This noise impact is much more noticeable in 2009 (when tourism activity may have been higher) as compared to 2011. Although gray whale calls can be 20–30 dB above background noise levels, their relatively low detection rates and short duration means that they occur less often than

panga transits during the "busy" whale-watching hours. For example, whale calls theoretically occur 0.7% of the time in the middle zone at any given hour, while panga transits can empirically be detected up to 10% of the time during pre- and post-lunch-time transits. The relative contribution of panga-generated sound to the lagoon's overall noise levels seems small compared to other whale-watching regions. Panga noise is most intense in regions where they are transiting with passengers–not where actual whale-watching is taking place, and not in the nursery environment. Even in the transit areas, pangas are usually only detected 10% of the time, and their SPL levels are still lower than those generated by snapping shrimp in the upper zone nurseries, and their occurrence is less common than the noise spikes generated by croakers each evening.

Finally, the various physical and biological contributions to the acoustic environment have remained stable in the middle zone over 6 years of observations, and in the upper zone over 2 years of observations. Indeed, the ambient environment for the middle zone is similar to the environment measured nearly 30 years ago, down to the existence of a noise minimum at around 300 Hz.

Expanding this dataset into the future is desirable. The zonation is satisfactory as is, although more years of data from the upper zone would be beneficial, and a deployment spot in the lower zone where recorders do not run the risk of getting lost would be ideal. An interesting future application of this work would be to estimate relative levels of tourist activity across years by flagging noise events at the percentile level indicative of the panga traffic's footprint. Anecdotal evidence suggests that tourism activity in 2009 was higher than in 2011, consistent with the relative levels of panga activity reported here, but a more formal comparison should be possible as more panga and acoustic information become available. If tourism increases in the future as the access road is paved, will the pangas' acoustic footprint increase? Continued work on these topics could permit passive acoustic monitoring to become a useful monitoring and oversight tool for managers and regulators of this unique and enchanting lagoon, and could provide a controlled environment for testing the ability of passive acoustics to detect small vessel activity in other marine protected areas.

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